Design of Water Diversion Structures Based Optimization Approach

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Abstract

Diversion structures such as barrages (diversion dams) and weirs are integral part of water resources infrastructure development of a country; they are the main component of any canal head work. Most procedures of design adopt the profile dimensions sanctioned by common practice; however, there is no specific procedure to fix the basic parameters in a cost-effective manner. Present work discusses the procedure of optimal design using Genetic algorithm (GA), an optimization-based methodology is presented to obtain the optimum dimensions that minimize the overall cost as well as satisfy the safety and functionality requirements. A parametric study was accompanied to identify the change in the barrage cost and profile dimensioning due to change in design conditions. Results show that the proposed optimization approach is capable of finding economic and safe design of the barrage. Among the design parameters, the flood discharge proved to have the greatest effect on the overall cost of the barrage, since a 20% increase in its value causes the cost to be increased by (16%); moreover, it showed that a barrage constructed on fine-grained soil is costlier than that constructed on a foundation of coarser bed material.

Keywords: Nonlinear Optimization Problem, Genetic Algorithm, Barrages, Parametric Study, Percentage Difference Method.

1. Introduction

Barrages and weirs are among the most common hydraulic structures, both types of structures have been used for more than thousands of years for water diversion purposes in the canal works. A safe and economic design of hydraulic structures is always being a challenge to water resources researchers. Barrages are used for delivering water for various purposes such as irrigation, water supply, navigation etc. They store large quantity of water making these projects extremely costly.

The characteristics of flow conditions are taken into considerations while designing a barrage. The crest level, Downstream (d/s) floor length, and minimum depths of Upstream (u/s) and d/s sheet-piles/cutoffs are mainly governed by surface flow considerations, while the length of the floor and its thickness is governed by subsurface flow conditions [1].

Optimization methods have been proved of much importance when used with simulation modeling and the two approaches when combined give the best results [2]. This study makes an attempt to formulate a nonlinear optimization problem that minimizes unit cost of concrete work, sheet-piling, protection works, gates and earthwork and searches the barrage dimensions that insure safety against seepage and surface flow induced failure of the hydraulic structure. The optimization problem is solved using Genetic algorithm (GA) method, the work is then extended to characterize variation in total cost and profile dimensions due to variation in the value of design parameters.

2. Hydraulics of the Barrage

2.1 Subsurface Flow

The subsurface flow or seepage occurs below the barrage floor because of the difference between u/s and d/s water level, it is prevailing for closed gates condition but also exits during other flow conditions. The method of independent variables proposed by Khosla et al. (1936) is commonly adopted for design of barrages against seepage; it is applied to compute the uplift pressure distribution and the value of the exit gradient at the d/s end of barrage floor [3].

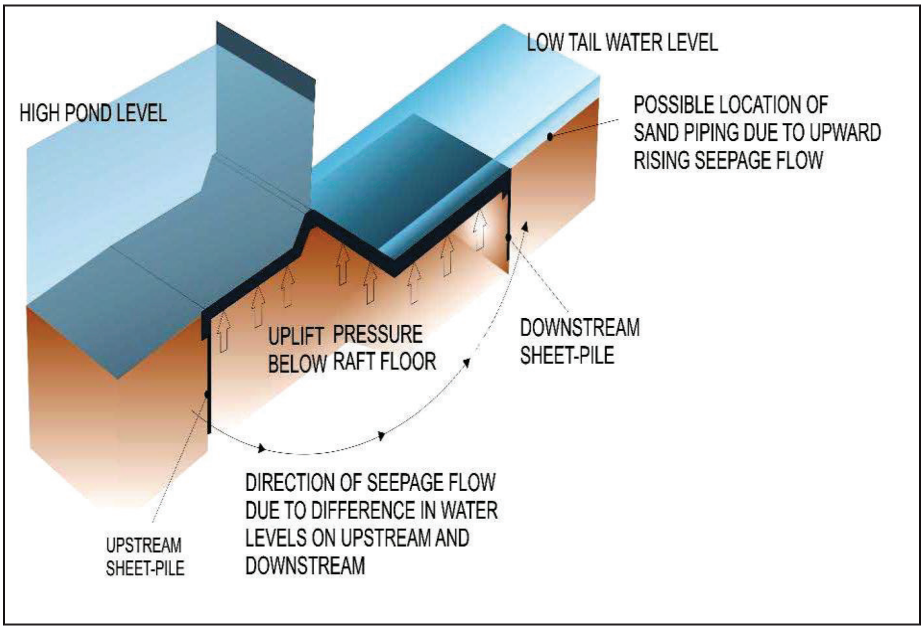

Figure 1. Seepage forces below barrage floor [4].

2.2 Surface Flow

A barrage constructed across a river has to pass floods of different magnitudes each year and the gates have to be operated in such a way that the water level in the pool is kept at least at the Pond Level (PL). A very high flood would require opening of all the gates to provide an almost obstruction-less flow to the flood. For smaller floods, the gates may not have to be opened fully to provide unobstructed flow. In some rivers the construction of a barrage causes the d/s riverbed to get degraded to progressively up to a certain extent, a phenomenon that is called Retrogression, which has been found to be more pronounced in alluvial rivers carrying more silt or having finer bed material and having steep slope. Because of retrogression, low stages of the river are generally affected more compared to the maximum flood levels. For the same flood discharge, a non-retrogressed river may exhibit submerged flow phenomenon (Figure 2-a) compared to a free flow condition (Figure 2-b) expected for a retrogressed condition. Therefore, there would be a difference in scour depths in either case [4].

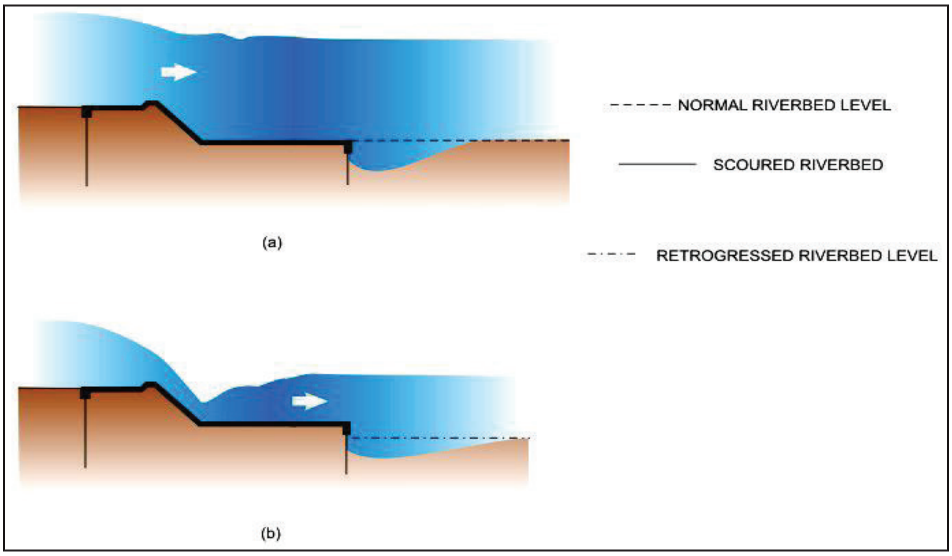

Figure 2. Flow modes in a barrage for the same discharge.

(a) Submerged flow (b) Free flow [4].

3. Mathematical Programming

3.1. Optimization Model

Hydraulic design of the barrage involves fixing the dimensions of component parts via the available formulae from a standard design code that assure safety against the expected failures [5]. This optimization model aims to determine the basic dimensions of a barrage (afflux, spillways span, floor length, u/s and d/s sheet-piles depth. The objective is to minimize the total cost of the construction of the barrage.

The constraints of the optimization model is that: the observed afflux at the design flood shouldn't exceed the maximum permissible afflux, the provided depth for sheet-piles in u/s and d/s should not be less than that required from scour considerations, the length of the floor and the depth of d/s sheet-pile should be such that the exit gradient is well within the safe exit gradient (SEG). Finally, the d/s velocity should be kept to a limiting value.

Upper and lower bounds representing possible ranges of values can be executed on the design variables to limit the search space within accepted values. The optimization model can be stated as in below:

$$C(X) = c_1(f_1) + c_2(f_2) + c_3(f_3) + c_4(f_4) + c_5(f_5) + c_6(f_6) + c_7(f_7) - c_8(f_8) + c_9(f_9) \quad (1)$$

Subjected to

$$h_a - x_1 \leq 0 \quad (2)$$

$$d_1 - x_3 \leq 0 \quad (3)$$

$$d_2 - x_4 \leq 0 \quad (4)$$

$$b - x_5 \leq 0 \quad (5)$$

$$v_a - v_l \leq 0 \quad (6)$$

$$x_1^l \leq x_1 \leq x_1^u \quad (7)$$

$$x_2^l \leq x_2 \leq x_2^u \quad (8)$$

$$x_3^l \leq x_3 \leq x_3^u \quad (9)$$

$$x_4^l \leq x_4 \leq x_4^u \quad (10)$$

$$x_5^l \leq x_5 \leq x_5^u \quad (11)$$

where C (x_1, x_2, x_3, x_4, x_5) is objective function represents total cost of barrage spillways section in unit price (U.P.), and it is function of the design variables that would be optimized as follows:

x_1 : Maximum permissible afflux (m).

x_2 : Gated spillway span (m), integer variable.

x_3 : Depth of the u/s sheet-pile (m).

x_4 : Depth of the d/s sheet-pile (m).

x_5 : The impervious floor length (m).

The functional parameters (f_1, f2, …, f9) involved in the objective function for a typical profile in a barrage spillways section is outlined herein:

f_1 : Total volume of concrete for a given barrage profile, (m^3).

f_2 : Area of sheet-piling below concrete floor in u/s side, (m^2).

f_3 : Area of sheet-piling below concrete floor in d/s side, (m^2).

f_4 : Quantity of cement concrete blocks for the block apron, (m^3).

f_5 : Quantity of gravel required under the block apron on the d/s side, (m^3).

f_6 : Quantity of stones/boulders for the flexible apron, (m^3).

f_7 : Total volume of excavated soil, (m^3).

f_8 : Total volume of soil required in filling, (m^3).

f_9 : Weight of the gates, (kg).

The prices of materials and all entries required to evaluate the cost of a barrage profile in unit price (U.P.) is explained below:

c_1 : Cost of concrete (labor and material), (unit price/m^3).

c_2 : Cost of u/s sheet-piling includes driving, (unit price/m^2).

c_3 : Cost of d/s sheet-piling includes driving, (unit price/m^2).

c_4 : Cost of cement concrete blocks, (unit price/m^3).

c_5 : Cost of graded gravel for inverted filter, (unit price/m^3).

c_6 : Cost of stones or boulders, (unit price/m^3).

c_7 : Cost of excavation with dewatering , (unit price/m^3).

c_8 : Cost of earth filling, (unit price/m^3).

c_9 : Cost of a gate, (unit price/kg).

$x_1^l, x_2^l, x_3^l, x_4^l$ and x_5^l are lower bound on x_1, x_2, x_3, x_4, x_5 respectively; $x_1^u, x_2^u, x_3^u, x_4^u$ and x_5^u are upper bound on x_1, x_2, x_3, x_4, x_5 respectively.

3.2. Characterizing Model Functional Parameters

For a specified barrage profile geometry (Figure 3) and hydrological conditions, the functional parameters f1, f2, f3,f4, f5, f6, f7, f8 and f9 involved in optimization model represented by (Equations 1, 2, …, 11) is computed by assuming a steady state subsurface flow below barrage floor and a free flow over barrage crests in case of a flood discharge. Both objective function and constraints are nonlinear; make the problem in the category of nonlinear optimization formulation. Characterization of functional parameters is available in literature [6].

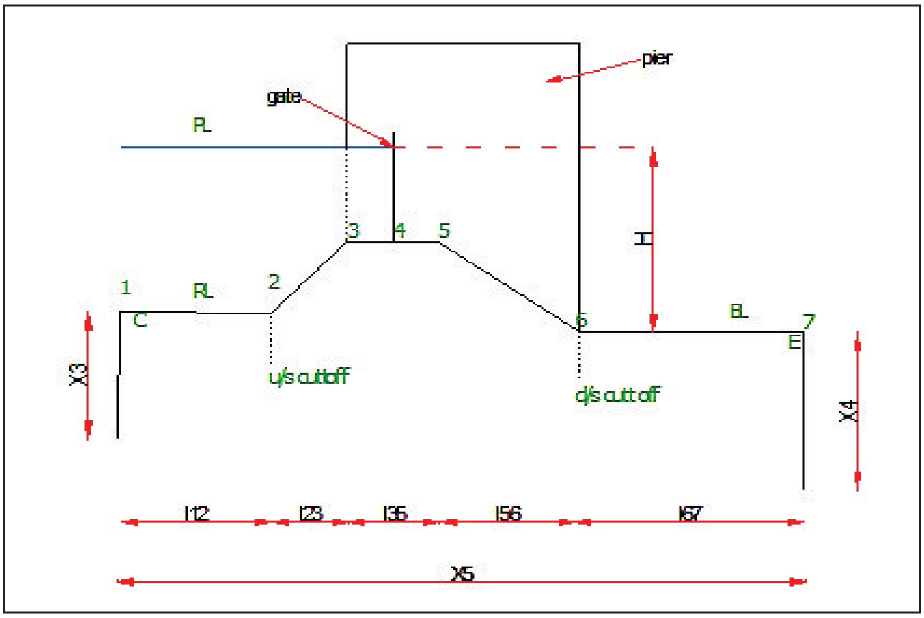

Figure 3. Schematic of barrage profile used in optimization process.

The optimization model represented by (Equations 1-11) is applied for a hypothetical case study and solved using genetic algorithm (GA) on MATLAB platform version (8.3.0.532); the basic steps employed are available in [6]. Table 1 shows results obtained by GA based optimization for Fig. 3, total cost of the structure is estimated for the provided dimensions and unit prices of the materials.

Table 1: GA optimization results.

Parameters, [m]	Design method
	GA optimization
x_1	0.38
x_2	10
x_3	3.79
x_4	5.15
x_5	37.33
Overall cost [U.P.]	234970

3.3. Procedure of Optimizing By Genetic Algorithm

Genetic Algorithm (GA) is an optimization method that simulates the evolution of natural genes to find approximated solutions to optimization problems. It could be applied to different types of problems that could not be solved by traditional methods; it does sequent steps in an iterative manner to converge at an optimal solution [7]. The process of optimizing by genetic algorithm for the problem proposed in this study is explained as a flow chart and showed in Figure4.

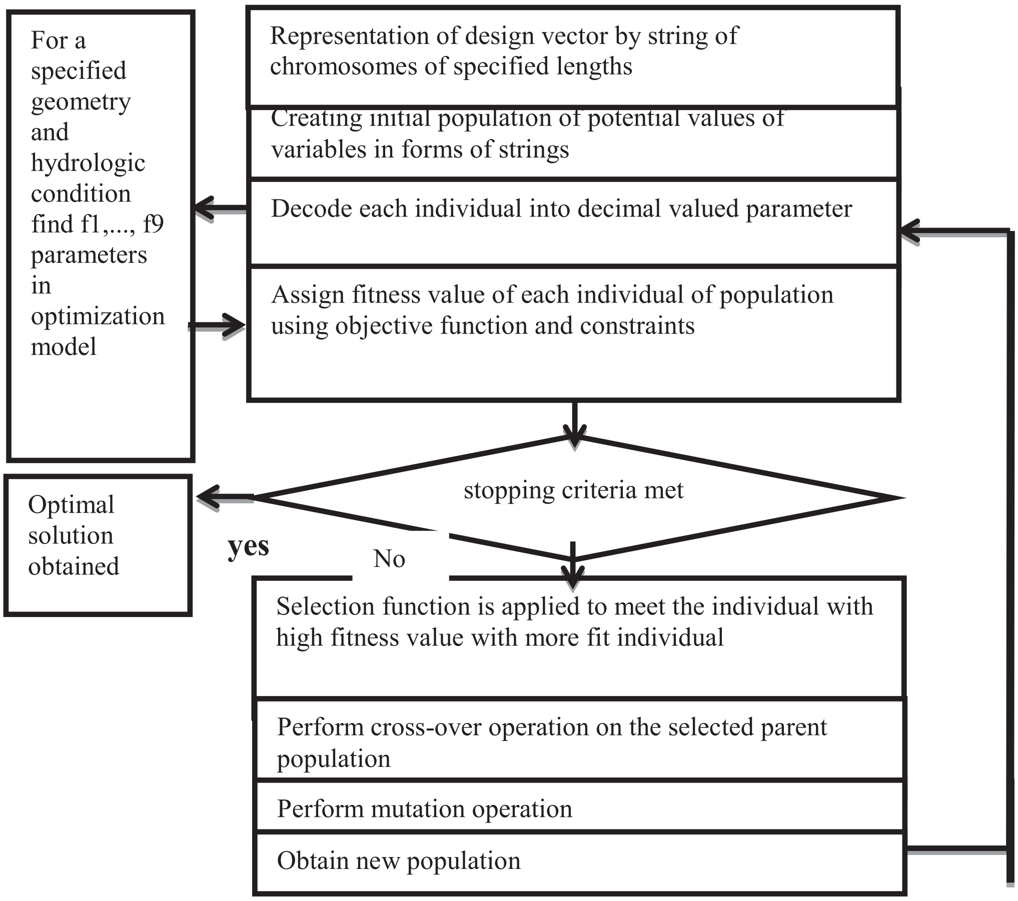

Figure 4. The flow chart of GA-based optimization.

4. Parametric Analysis

In the optimization model of barrage hydraulic design, the incorporated parameters represent the conditions under which the structure is to work that govern the dimensions of the barrage profile thus govern the overall cost. These parameters are:

Q_{des} : Design flood discharge (m^3/sec).

H : Seepage head (m).

SEG : Safe exit gradient for riverbed material.

r : Riverbed retrogression (m).

f : Silt factor (m).

tmin: Minimum assumed floor thickness (m).

Zcrest : Crest level of a spillway bay (m).

L23 : Horizontal length of u/s glacis (m).

Wp : Width of piers (m).

4.1. Effect of Design Parameters on the Barrage Total Cost

To compare the effects of the design parameters on the overall cost of a barrage, the form percentage difference is used. It describes the change in the barrage cost due to percentage change in a parameter by numerical terms that give engineering values. The method of percentage difference can be defined as below [8]:

$$\%difference = (x - x_{ref})/x_{ref} * 100 \quad (12)$$

X =explored value of a design parameter.

Xref =reference value of a design parameter.

The optimal design was first obtained assuming a deterministic value for each design parameter (Table1) then a number of analyses have been worked out, each analysis uses a chosen set of input parameters, to find design variables values and total cost of the barrage. Each parameter was taken separately while the others persisted constant, MATLAB program version (8.3.0.532) is adapted to be able to implement this analysis. The values of design parameters used in this exploration are shown in Table 2.

Table 2: Values of design parameters used in the analysis.

Design Parameter	Symbol	Unit	Reference value Table (1)	Investigated values
Flood discharge	Qdes	m3/sec	8500	2000, 4000, 6000, 8000,8500
Seepage head	H	m	5.5	4, 5.5, 7.5, 10, 12
Safe exit gradient	SEG	dimensionless	1/6	1/8, 1/7, 1/6, 1/5, 1/4
Retrogression	r	m	0.5	0.3, 0.5,0.8, 1, 1.25
Silt factor	f	m	1	0.6, 0.85, 1, 1.25, 1.5
Minimum floor thickness	tmin	m	1	1.5, 1, 0.75, 0.5, 0.25
Crest elevation	Zcrest	m	101.25	101, 101.25, 101.5, 102, 103
U/s glacis length	l23	m	6.25	2.5, 3.75, 5, 6.25, 7.5
Pier width	WP	m	1.5	1, 1.5, 2, 2.5, 3

Therefore, a graph could be constructed in which percentage difference of each design parameter is the X–axis and percentage difference of the total cost value is the Y–axis, the line that is joining the corresponding values depicts the effect. A graph for the percentage difference of change in deign parameters with the percent of change in barrage total cost is shown in Figure 5.

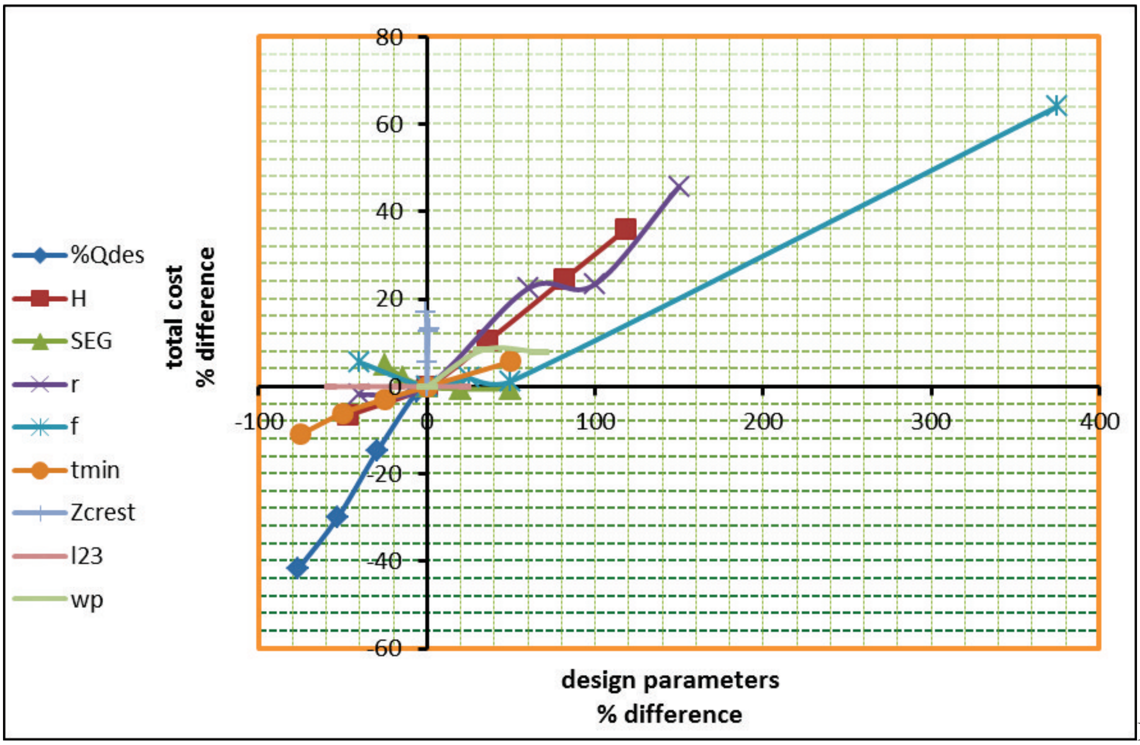

Figure 5. Percentage change in design parameters vs. overall cost.

Assumed (20%) increase and decrease (from reference values in table 2) in the values of the design parameters with relative percentage differences in overall cost are ordered in Table 3 and shown below:

Table 3: Effect of 20% increment and decrement in design parameters values on barrage Cost.

20% increase in design parameter value	% change in barrage cost	20% decrease in design parameter value	% change in barrage cost
Qdes	16.1867	Qdes	-11.108
H	5.55	H	-4.734
SEG	-0.5239	SEG	3.5345
r	4.338	r	-0.976
f	2.0377	f	1.4423
tmin	2.288	tmin	-2.291
l23	-0.00553	l23	0.0719
Wp	3.633	wp	-0.7388

4.2. Effect of Design Parameters on the Barrage Profile Dimensions

The change in each design parameter value is expressed in a percentage form and sketched against the corresponding percent of difference in each design variable value to detect the significance of each design parameter on the barrage profile dimensions, as shown in Figure 6.

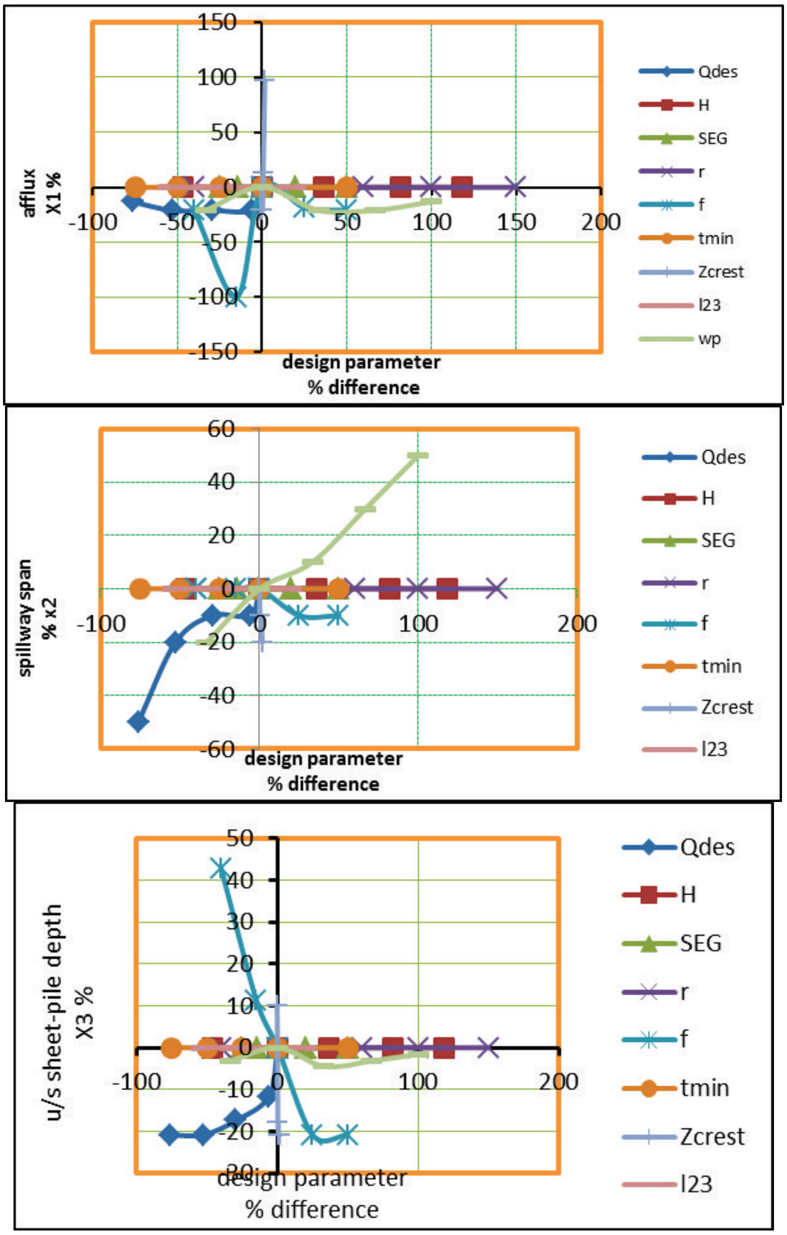

Figure 6. Percentage effect of the design parameters on the barrage dimensions.

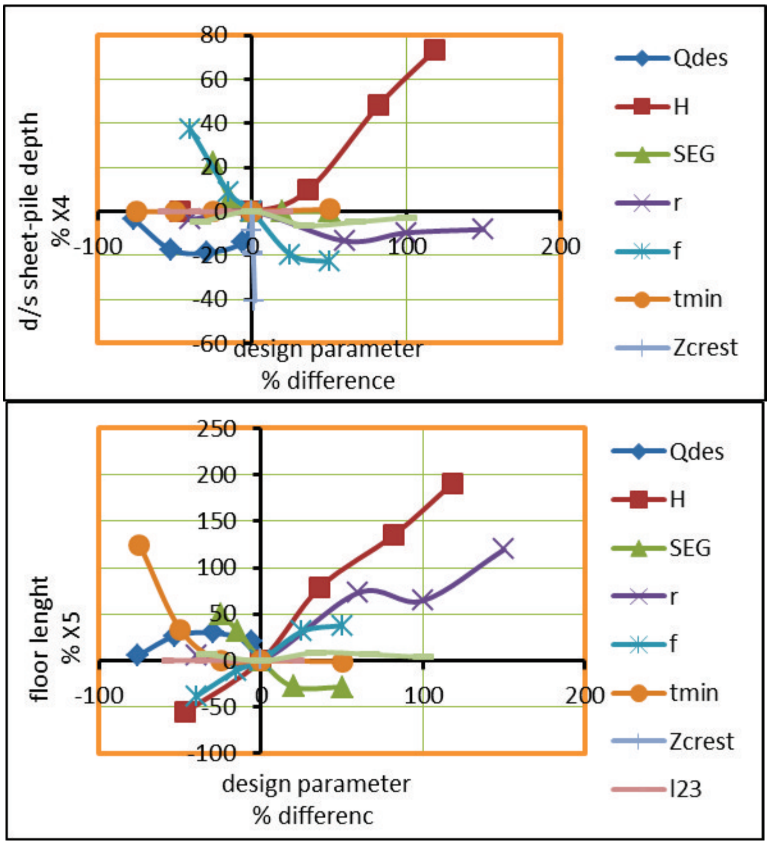

Figure 6. Percentage effect of the design parameters on the barrage dimensions (continued).

A sample of 20% increasing and decreasing in the parameters values associated with the changes caused in the barrage dimensions are shown in Table 4.

Table 4: Effect of 20% difference in design parameters on barrage profile dimensions.

20% increase in design parameter value	% difference in barrage dimensions				
	X1	X2	X3	X4	X5
Qdes	-21.0526	-10	-6.0686	-7.37864	10.47415
H	0	0	0	2.330097	46.79882
SEG	0	0	0	0	-27.9132
r	-21.0526	-10	-6.0686	0.776699	-1.01795
f	-21.0526	-10	-20.3166	-20.1942	32.54755
tmin	0	0	0	0	0
l23	0	0	0	0	0
Wp	-5.26316	10	-0.79156	-1.16505	1.580498

Table 4: Effect of 20% difference in design parameters on barrage profile dimensions (continued).

20% decrease in design parameter value	% difference in barrage dimensions				
	X_1	X_2	X_3	X_4	X_5
Q_{des}	-21.0526	0	-2.37467	-4.07767	5.571926
H	0	0	0.791557	0	-37.8248
SEG	0	0	0	13.39806	41.46799
r	0	0	0	-1.94175	2.652023
f	-21.0526	0	16.62269	13.39806	-15.8318
t_{min}	0	0	0	0	0.026788
l_{23}	0	0	0.791557	12.23301	0.187517
W_p	-21.0526	-20	-6.86016	-8.15534	11.59925

5. Discussions

It can be noticed that the design flood discharge is the most significant design parameter in determining the total cost of a barrage, followed by the other parameters as given in Table 3 and understandable from Fig. 5. In addition to that, the design flood discharge, as a hydrological parameter, is more effective than the seepage head, since an increment of (20%) in the flood discharge value leads to a (16.1867%) increase in total cost as compared with a (5.55%) increment due to the seepage head for the same increment percentage as shown in Table 3. For the parameters that relate to foundation soil type, it can be seen that for the same percentage change the retrogression of river bed is more effective than the safe exit gradient and the silt factor as shown in Fig. 5 and Table 3. The increment in width of piers leads to increased concrete volume and thus increased cost more than the cost from increased minimum floor thickness as parameters of barrage profile geometry as shown in Fig. 5 and Table 3.

On the other hand, the crest elevation (Z_{crest}) of a barrage spillway has the greatest effect on the permissible afflux, since a (1.73%) increase in the crest elevation cause an increase of (97.37%) in the permissible afflux. The flood discharge, crest elevation and the pier width are the most important parameters in deciding spillway span. Sheet-piles depth is governed by silt factor mainly since increasing its value leads to a decrease in this depth, but the d/s sheet-pile depth rises as increasing in seepage head (H) and reduction in silt factor (f) and safe exit gradient (SEG). No effect for seepage head and safe exit gradient on u/s sheet-pile depth. It can be seen that the seepage head, silt factor, minimum assumed floor thickness and the safe exit gradient of riverbed foundation are the most important parameters in calculation of barrage floor length.

6. Conclusions

The relative sensitiveness of the barrage overall cost and dimensions to the design parameters was shown by the form percentage difference, which gives an indication about the importance of each design parameter. Among the design parameters, the flood discharge (Qdes) proved to have the greatest effect on the total cost of the barrage, since a 20% increase in its value causes the cost to be increased by (16%). For different values of the design parameters considered in the study, the total floor length is mainly governed by the seepage head and the safe exit gradient of foundation soil whereas The upstream and downstream sheet-piles depth is highly sensitive to the value of the silt factor. The GA based optimization approach is equally valid for optimal design of other major hydraulic structures.

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